Private vs. public value of U.S. residential battery storage operated for solar self-consumption

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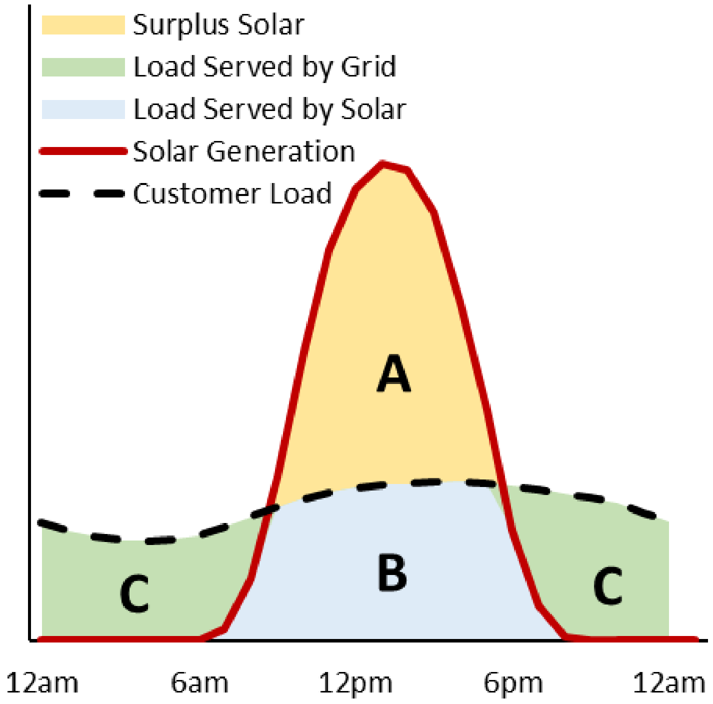
Context and Motivation

- Net billing has emerged as the *de facto* successor to net metering in many jurisdictions
- Its defining feature is an **asymmetric pricing structure**: solar generation can offset contemporaneous load at the full retail rate (Area B), but any surplus solar exported to the grid (Area A) is compensated at a specified grid export rate, typically less than the retail rate
- Creates an incentive to use battery storage to **arbitrage** between retail and grid-export prices, by shifting surplus solar generation to meet load (Area C)



Questions:

- *What benefit does this arbitrage behavior provide to the electric system?*
- *And how does that compare to the private benefit received by the solar+storage customer?*

Analysis Overview

Objective: Quantify the value of residential storage dispatched for solar-self consumption from both the private (host customer) and public (electric system) perspectives

- Relies on unique empirical dataset of metered hourly load data from ~1800 residential customers across a diverse set of geographies and market conditions
- Considers wholesale energy costs as well as “peak-related” system costs across the generation, transmission, and distribution systems
- Focus is on current/historical market conditions, but also considers futures with considerably higher renewable penetration levels on the grid
- Compares outcomes primarily in terms of market value of storage, but also in terms of grid export levels (relevant both for solar self-consumption and also as an indicator of potential stress on the local distribution network)

Organization

- **Data and methods**
- **Core results**
  - Based on metered hourly load data and market prices for the same locations and time periods
  - Estimate private and public value across a range of assumptions
  - Compare to market value if storage were operated optimally from power system perspective (the “value gap”), given historical market prices
- **Decomposing the value gap**
  - Distinguish between the effects of time varying rates, grid charging/discharging constraints, and asymmetric pricing
  - Show how more beneficial outcomes could be achieved by introducing hourly prices and with some allowance for grid charging/discharging
- **Assessing the persistence of the value gap in high-renewables futures**
  - Use simulated market prices to show how the value gap evolves as the market price profile shifts (i.e., begins to resemble the proverbial “duck curve”)
- **Conclusions**

Data and Methods

Data and Methods (Core Analysis)*

Load Data: Metered hourly loads from ~1800 residential customers *without* PV or storage, across 6 utility service territories, from 2012-2013

Solar Profiles: Simulated using NREL's System Advisor Model for the same locations and time period as the load data

Market Data: Day-ahead energy market prices and balancing authority system loads for the same locations and time period as the customer load data

Key Assumptions: Base-case assumptions and scenarios for (a) PV & storage sizing, and (b) retail tariff design

Storage Dispatch Model: Dispatch storage to either (a) minimize solar exports or (b) maximize market value

Outputs: Energy + peak value of storage and customer bill savings, in units of ***$ per kWh of storage capacity per year***; also grid export levels

**Several supplemental analyses were performed with other datasets, as described elsewhere*

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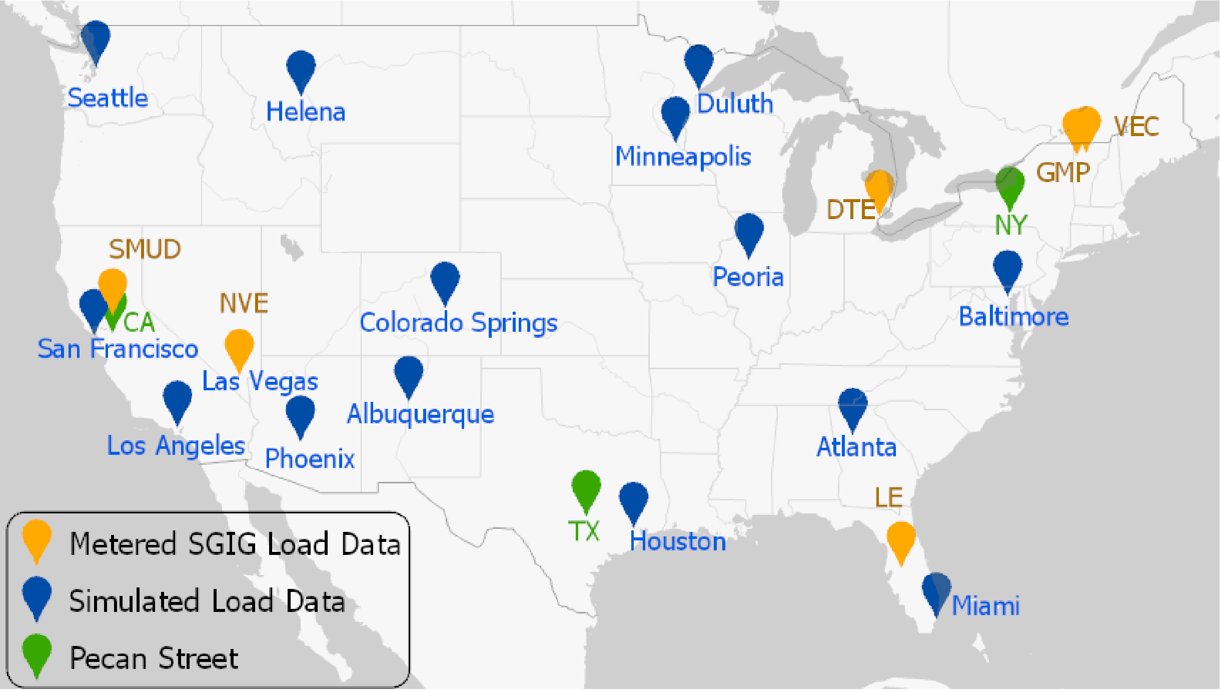
Side Bar: A word on PV and storage sizing in this analysis

- Throughout the analysis, we refer to PV and storage sizes in <u>normalized</u> units, in order to facilitate comparison across individual customers
- PV sizing
  - Denominated in terms of PV annual generation as a fraction of annual customer consumption
  - We explore results across PV system sizes
  - Many parts of the analysis focus on a PV system size of **1.0**, that is, where the PV system is sized to generate 100% of annual customer load; equates to 4-8 kW across most customers
- Storage sizing
  - Denominated as a fraction of average daily PV generation
  - We explore results across storage sizes (varying kWh capacity, and assuming 2-hour duration)
  - Many parts of the analysis focus on a storage size of **0.5**, that is where storage energy capacity is equal to 50% of average daily PV generation (typical of current residential systems, and equates to about 10-15 kWh of storage, for the standard PV size noted above)

Load Data: Additional Details

- Primary analysis relies on metered load data from six utilities, collected through the Smart Grid Investment Grant (SGIG) Program
  - Detroit Edison (DTE)
  - Green Mountain Power (GMP)
  - Lakeland Electric (LE)
  - Nevada Energy (NVE)
  - Sacramento Municipal Utilities District (SMUD)
  - Vermont Electric Cooperative (VEC)
- Secondary/supplemental parts of the analysis rely on two other load datasets:
  - Simulated hourly load profiles from EnergyPlus simulations of DOE standard residential building models in 15 locations (used in section "Assessing the Persistence of the Value Gap")
  - One-minute-interval load data obtained from Pecan Street for 265 customers in 3 states (used for sensitivity in Appendix)

Customer load data locations



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Core Results

Some Initial Assumptions (to be relaxed later)

1. Flat retail prices for both consumption and exports
2. Storage only charges from surplus solar, and only discharges to meet load (i.e., no grid charging or grid discharging)
   - Net billing naturally incentivizes this kind of operation
   - But other factors can also constrain grid charging/discharging (e.g., ITC, interconnection rules, tariff provisions, etc.)

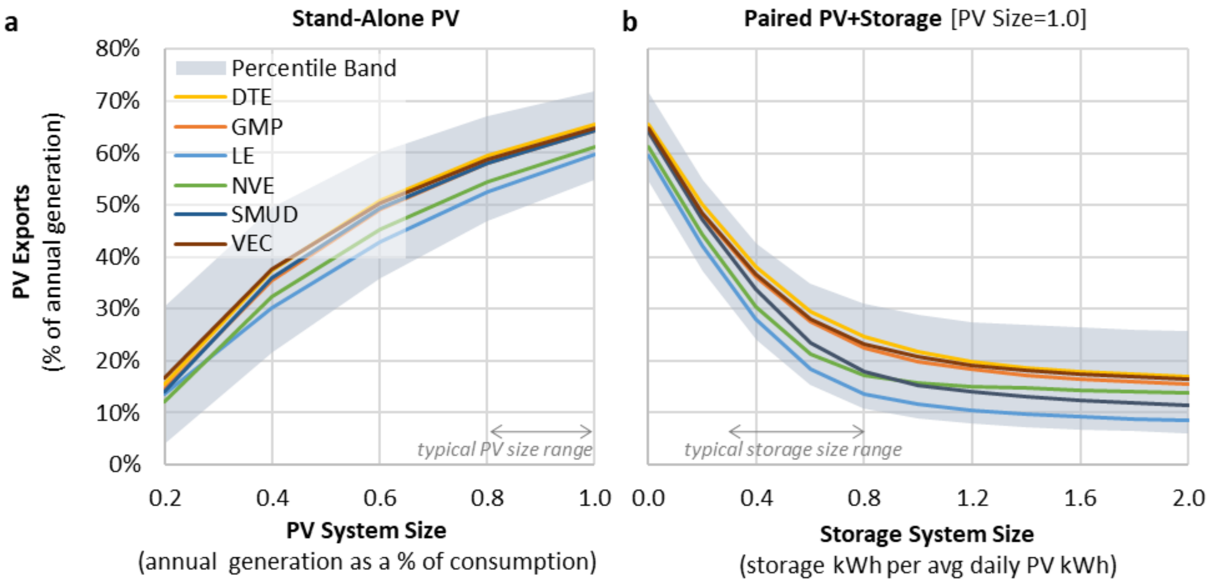
As will be shown later, these two assumptions are inter-related

- Time-varying rates matter most for the results when storage can freely charge from / discharge to the grid
- And similarly, charging/discharging constraints matter only if there are time-varying price signals of some form

Solar PV Grid Exports with and without Battery Storage

Storage can shift most, but not all, PV grid exports (roughly two-thirds, for a typical sized system)

- Grid exports increase with PV system size
- For stand-alone PV within a typical size range, **47-72%** of annual PV generation is exported, across customers in the sample
- Storage could reduce grid exports to **11-31%** of annual PV generation, for storage systems at the upper end of sizes typically observed
- Larger batteries could reduce exports further, but with rapidly diminishing returns due to limits on the amount of nighttime load available for storage discharge

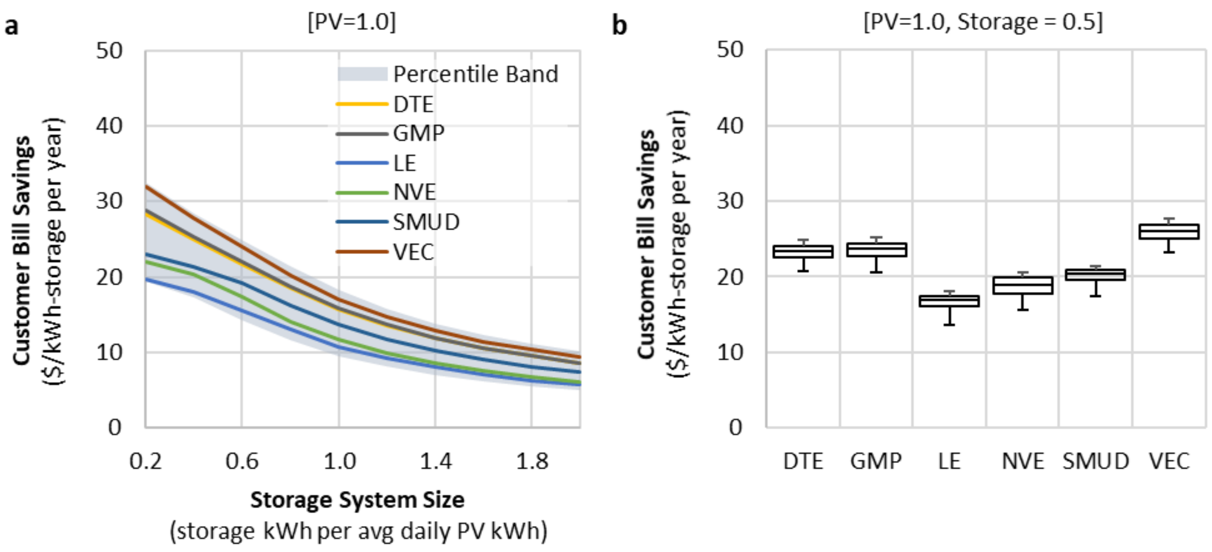


Notes: Panel **a** shows annual PV exports for systems without storage, across varying PV system sizes, while panel **b** presents annual PV exports for a relatively large PV system paired with battery storage of varying sizes and operated only to maximize solar self-consumption. PV export percentages are calculated as the sum total of exports within each hourly interval over the course of the year, divided by total annual solar generation. Solid lines represent median values across all customers of each utility, while the percentile bands represent the 5th to 95th percentile range across all customers of all utilities.

Customer Bill Savings from Operating Storage for Solar Self-Consumption (i.e., arbitrage between retail & export rates)

Incremental bill savings from increasing solar self-consumption are insufficient on their own to justify the up-front cost of storage

- Customer bill savings from solar export arbitrage exhibit diseconomies of scale with storage sizing (incremental storage capacity has lower usage)
- For a typical system configuration (right-hand figure), annual bill savings range from $17-26/kWh-storage across the six utility medians
- At current residential storage costs of $700-1300/kWh-storage, the bill savings are far from sufficient to justify the capital cost of storage (i.e., >20-year payback)



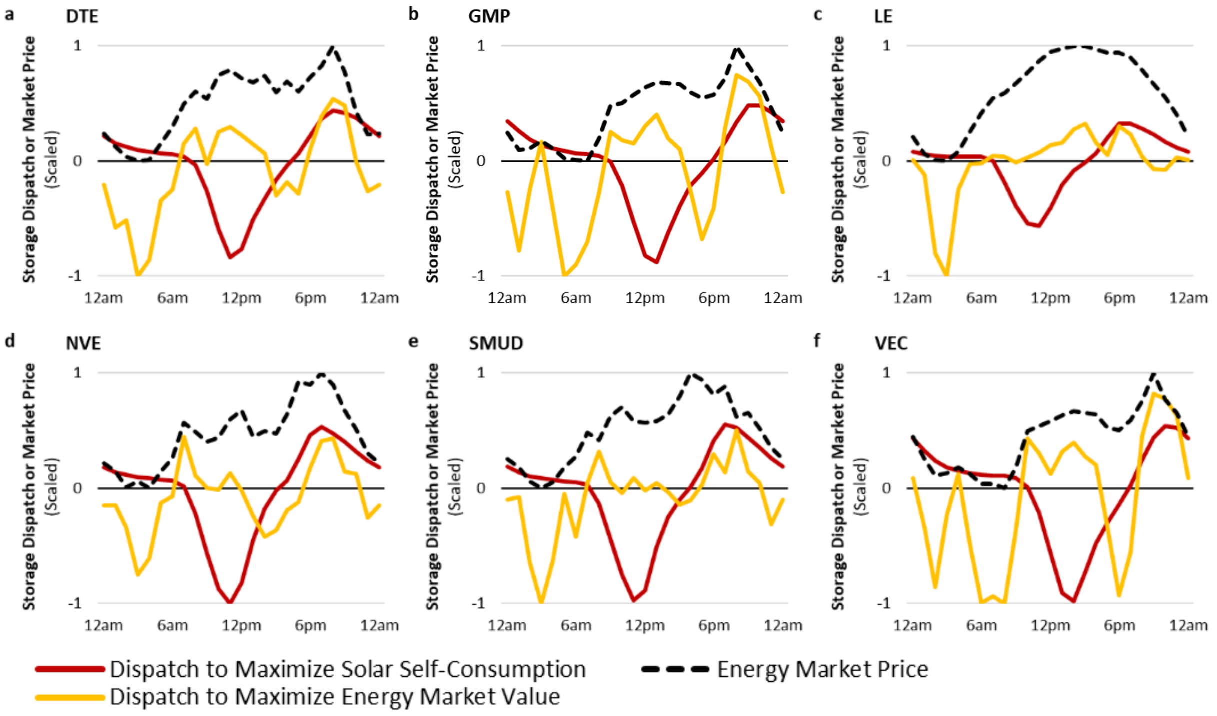
Notes: Panel **a** shows annual bill savings across a range of storage system sizes, while panel **b** presents the distribution in bill savings across customers of each utility, for a storage system sized at 50% of average daily PV generation. Here and elsewhere, storage dispatch value is denominated in units of $ per kWh of storage capacity ($/kWh-storage) per year. The bill savings are based on arbitraging solar export quantities between average retail and wholesale prices for each utility, with the constraint that only 80% of storage energy capacity can be utilized, in order to maintain minimum and maximum states of charge on the battery. In panel **a**, solid lines represent median values across all customers of each utility, while the percentile bands represent the 5th to 95th percentile range across all customers of all utilities. In panel **b**, the boxes present the 25th to 75th percentile range, and the error bands show the 5th and 95th percentile values across customers of each utility.

Alignment of Storage Dispatch and Energy Market Prices

Storage profiles when operated to maximize solar self-consumption (red lines) are poorly aligned with wholesale energy market prices

- Both charging and discharging are misaligned with energy market prices
  - Charging during daytime hours, when prices are relatively high
  - Discharging begins in the evening, when prices are relatively high, but continues through the night, when prices are at their lowest
- For comparison, yellow lines show storage dispatch profile if operated to maximize energy market value
- Later results consider market price profiles in futures with high solar penetration

Annual average dispatch profiles and market prices



Notes: The figures present annual average storage dispatch profiles for each of the six utilities, averaged across all customers and all days of the year, along with annual average energy market prices in each hour. Storage dispatch profiles are represented with a positive value for discharging and a negative value for charging, and are normalized to the maximum absolute value of each profile. Similarly, energy market prices are normalized to a max=1 and min=0.

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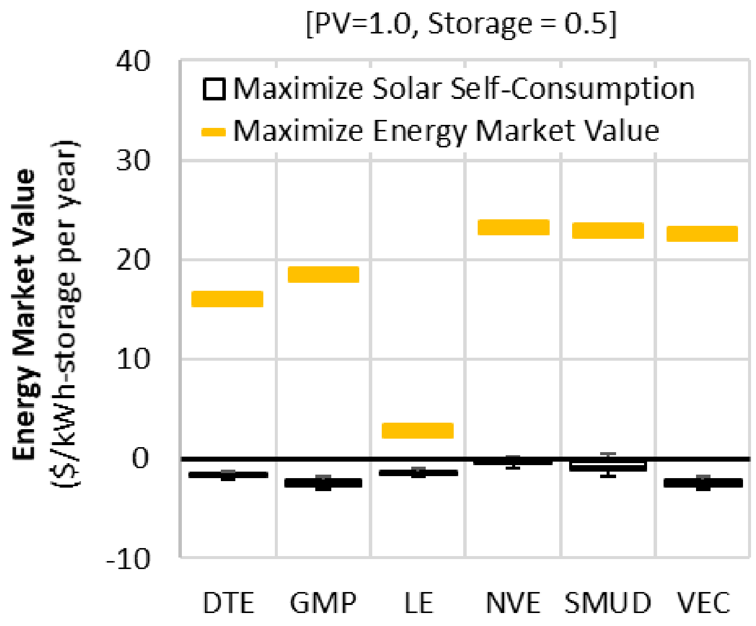
Energy Market Value of Storage Operated to Maximize Solar Self-Consumption

The energy market value of storage operated for solar self-consumption is effectively zero (actually, less than zero)

- This is the result of the misalignment between the temporal profile of storage dispatch and energy market prices, assuming flat rates (though later results show similar findings can occur with time-varying rates)
- Results are highly consistent across customers and utilities
- By comparison, storage dispatched to maximize its energy market value would yield a value of $16-23 per kWh of storage annually across all utilities except LE*



Notes: The figure compares the energy market value of storage dispatched to maximize solar self-consumption under time-invariant net billing rates to one in which storage is dispatched to maximize its energy market value. These results are based on a single, standard PV+storage system configuration. For the solar self-consumption case, results are presented as a box-and-whiskers plot showing the distribution across all customers of each utility, with boxes representing the 25th to 75th percentile range, and the error bands showing the 5th and 95th percentile values. For market dispatch case, the energy value is invariant across customers, and thus a single point value is provided for each utility.

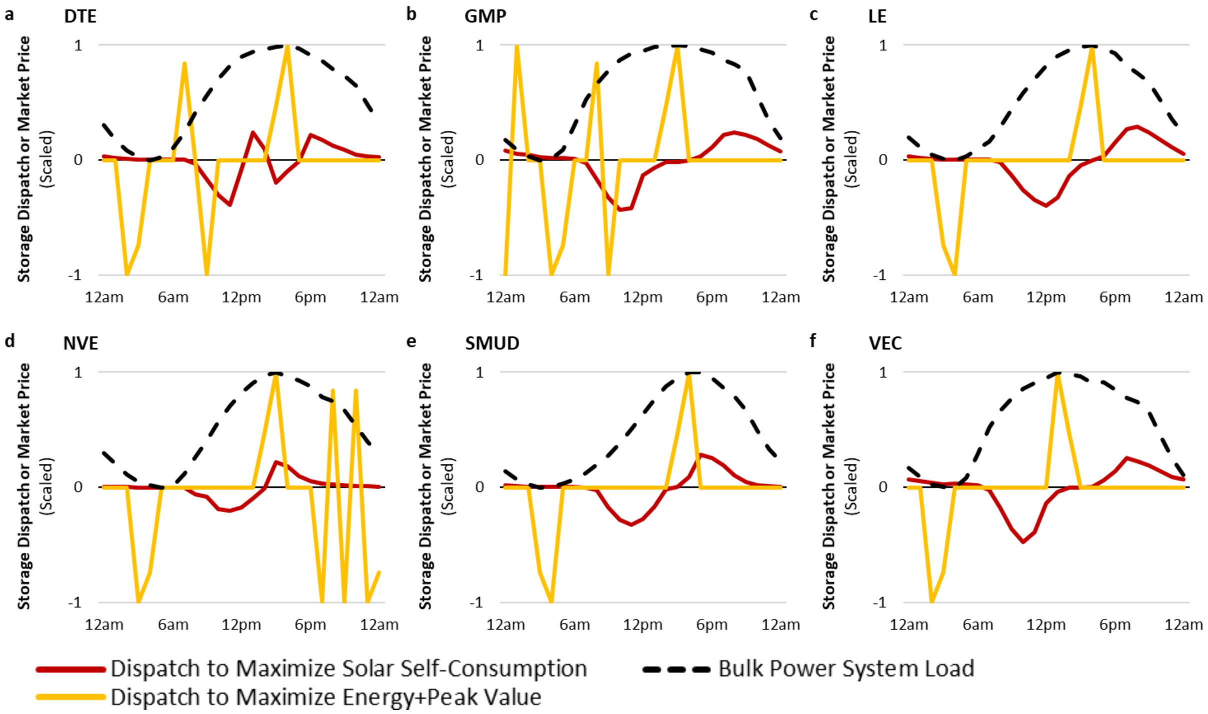
* LE energy market value is lower because it is not part of a regional power market, so hourly marginal energy costs are less volatile

Alignment of Storage Dispatch and System Peak Demand

Storage that is operated solely to maximize solar self-consumption (red lines) largely sits idle on peak-load days

- Individual solar customer loads are also high on system peak-load days, resulting in little surplus solar generation, and thus little energy available to fuel storage dispatch later in the day (when system peaks occur)
- Moreover, what little storage dispatch does occur is not well aligned with the system peak load hour
- For comparison, yellow lines show storage dispatch profile if co-optimized for both energy market value and system peak demand reduction

Storage dispatch profiles on system peak-day



Notes: The figures present storage dispatch profiles for each of the six utilities, on their single peak-load day, averaged across all customers and all days of the year, along with the system load profile for that day. Storage dispatch profiles are represented with a positive value for discharging and a negative value for charging, and are normalized to the maximum absolute value of each profile. Similarly, system loads are normalized to a max=1 and min=0.

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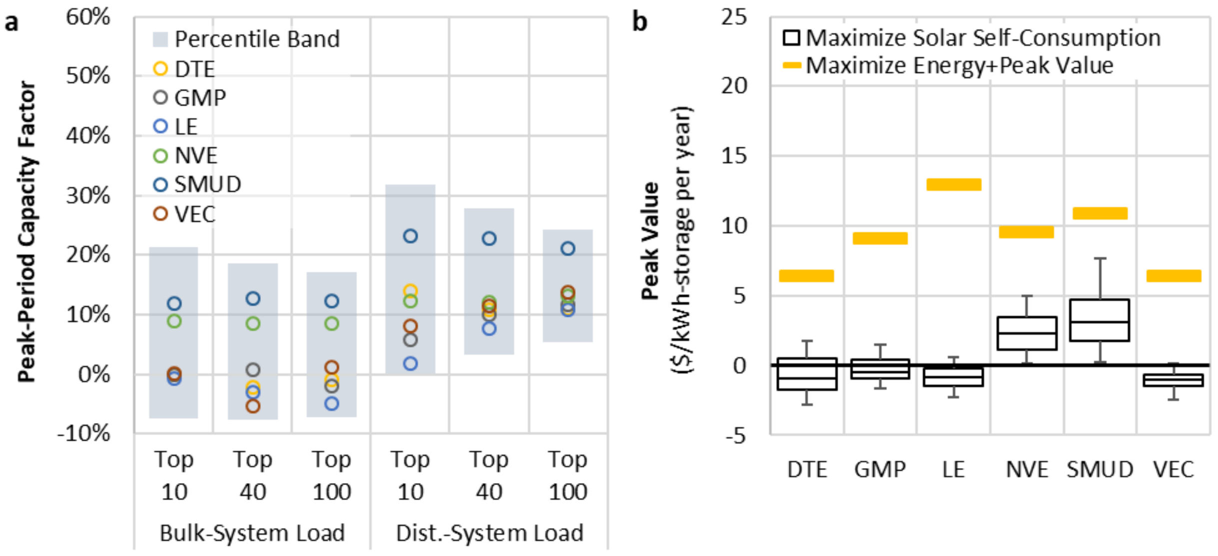
Peak Value of Storage Operated to Maximize Solar Self-Consumption

Storage operated for solar self-consumption provides little if any peak value

- Peak value encompasses a variety of power system costs driven by peak demand, including generation and T&D capacity
- Peak value of storage is the product of its coincidence with peak demand and marginal cost of meeting peak demand
- Storage operated for solar self-consumption has low peak coincidence (panel a), though somewhat higher relative to distribution peak
- At a marginal peak cost of $50/kW-year over the top-40 peak load hours, storage would provide a peak value of $6-13/kWh-storage in the best-case scenario (the yellow lines in panel b); much less if operated for solar self-consumption



Notes: Panel **a** shows peak-period capacity factors of storage operated for solar self-consumption under alternate peak-period definitions, based on either the bulk-power system load or the local distribution system load, and across the top-10, -40, or -100 hours. The circles represent median values for each utility, while the percentile bands show the range between the 5th to 95th percentile across all customers of all utilities. Panel **b** compares the peak value of storage dispatched for solar self-consumption relative to its value if dispatched to maximize its combined peak and energy-market value. Those peak values are based on a $50/kW-yr marginal capacity cost, allocated across the top-40 bulk-power system load hours. For the solar self-consumption case, results are presented as a box-and-whiskers plot showing the distribution across all customers of each utility, with boxes representing the 25th to 75th percentile range, and the error bands showing the 5th and 95th percentile values. For market dispatch case, the energy value is invariant across customers, and thus a single point value is provided for each utility.

Decomposing the Value Gap

Scenario Design to Decompose Contributing Factors

- The preceding "value gap" relative to market-optimized storage dispatch can be attributed to:
  - Asymmetric pricing between solar-self consumption and grid exports
  - Time invariant prices assumed for both solar self-consumption and grid exports
  - Restrictions on grid charging or discharging (related to ITC, interconnection rules, or tariffs)
- To disentangle the relative effects of each, we compute storage dispatch value over a structured sequence of scenarios that move incrementally (see green highlights) from our basic net billing tariff with flat prices to full market-based dispatch:

Scenario	Price Structure	Fixed $/kWh T&D Adder for Consumption	Grid Charging Allowed	Grid Discharging Allowed
1 (base)	Flat	Yes	No	No
2	**Hourly**	Yes	No	No
3	Hourly	Yes	**Yes**	No
4	Hourly	Yes	Yes	**Limited** (up to PV nameplate)
5	Hourly	Yes	Yes	**Yes**
6 (full market dispatch)	Hourly	**No**	Yes	Yes

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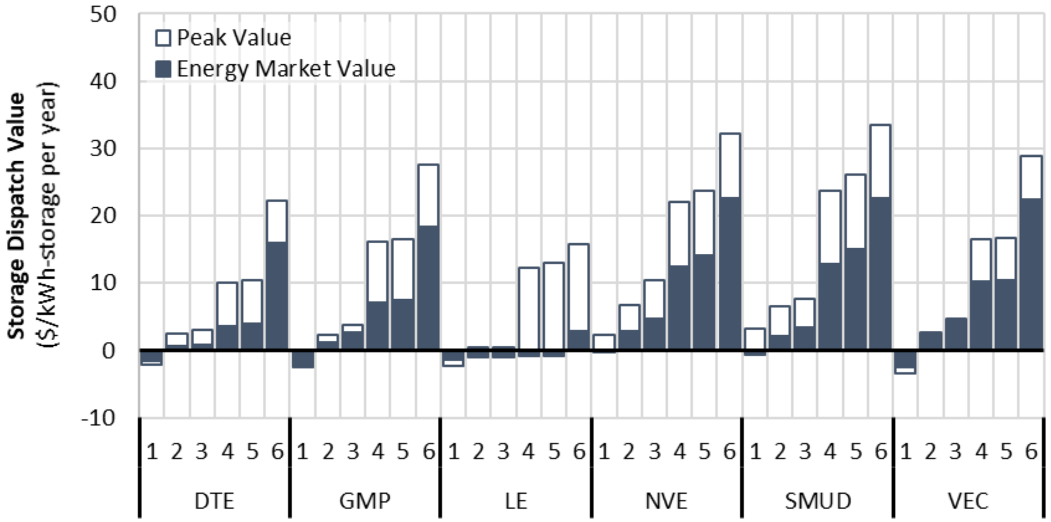
Storage Dispatch Value across Tariff Scenarios:
Key Observations and Implications

- The effect of time-invariant pricing, in isolation, is quite small → thus, even if timed optimally with market prices, storage dispatch for solar self-consumption yields little market value
- Constraints on grid charging have little effect
- Large step changes occur when constraints on grid discharging are relieved (assuming hourly pricing); especially true for peak value, which can be captured only if storage can discharge to the grid during peak hours (in this case, the top-40 peak load hours)
- Asymmetric pricing is responsible for 30-50% of the overall value gap, due entirely to its effect on energy value (associated mostly with routine daily cycling)



Notes: Plotted values are medians across all customers of each utility.

Scenario 1: Net billing with flat prices
Scenario 2: Net billing with hourly prices, no grid charging or discharging
Scenario 3: Net billing with hourly prices, grid charging allowed, no grid discharging
Scenario 4: Net billing with hourly prices, grid charging allowed, partial grid discharging allowed
Scenario 5: Net billing with hourly prices, grid charging allowed, full grid discharging allowed
Scenario 6: Market-based dispatch with hourly prices, grid charging and discharging allowed

All net billing scenarios maintain a fixed pricing differential between consumption and export prices. See slide 18 for further details.

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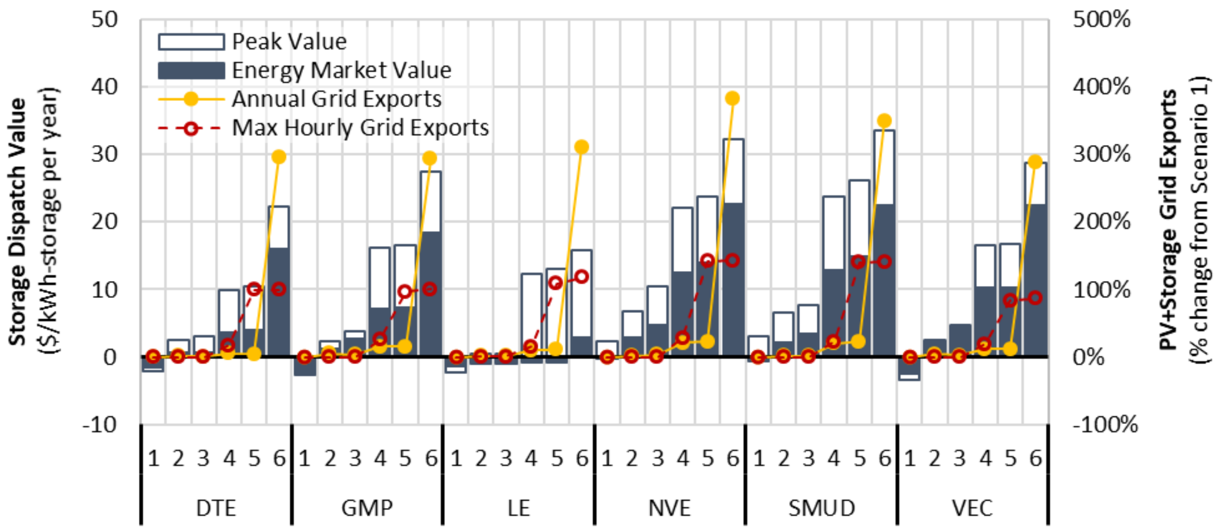
Grid Exports across Tariff Scenarios: *Key Observations and Implications*

- Two grid export metrics considered:
  - Annual (a measure of solar self-consumption)
  - Maximum hourly (indicator of local grid stress)
- Allowing unlimited grid discharge (Scenario 5) doubles the maximum hourly grid exports relative to cases with no grid discharge
- In contrast, allowing limited grid discharging (Scenario 4) avoids any notable increase in maximum hourly grid exports
- Eliminating the asymmetry in prices between exports and self consumption (Scenario 6) results in 4-5 times more annual grid exports, even greater than for stand-alone PV



Notes: Annual grid exports and maximum hourly grid exports are denominated as a percentage change from Scenario 1. See Slide 19 notes for additional details.

Scenario 4 is a sweet-spot: Achieves 50-70% of the potential market value, without significantly degrading solar self-consumption or imposing greater stress on the local distribution network

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Assessing the Persistence of the Value Gap

How does this analysis hold up in high-RE futures?

- With increasing renewable energy (RE) generation on the grid, wholesale energy market prices will begin to resemble the proverbial “duck curve”: low in the middle of the day and highest in the early evening hours
- In theory, this might align reasonably well with the dispatch profile of storage used to manage solar self-consumption
- To test this hypothesis, we re-ran our “core” analysis scenarios using projected hourly energy and capacity market prices thru 2050, from NREL’s Cambium model
  - 2020 Standard Scenarios, Low RE Cost Scenario, where combined solar+wind generation reaches 60% of total U.S. electricity generation
  - Consider 15 locations (see Data and Methods section for details)
  - Use simulated residential load profiles based on 2012 weather data (the same weather year used to create the solar and wind generation profiles in Cambium)

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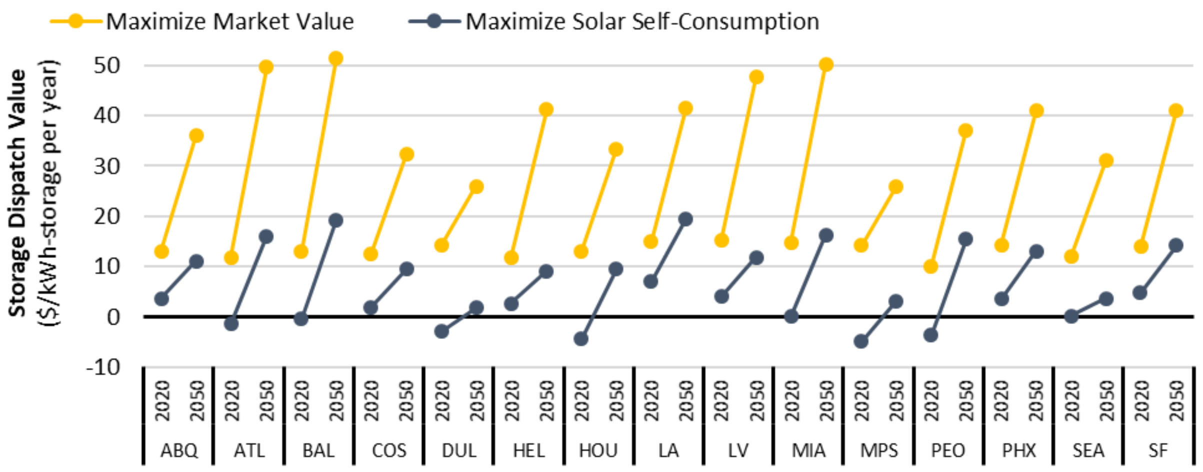
Storage Dispatch Value in a High-RE Future

The value of storage dispatched for solar self-consumption rises in high-RE futures, but the gap relative to market-based dispatch widens

- The market value of storage dispatched for solar self-consumption rises by $10/kWh of storage capacity, on average, over the 15 locations
- Yet, the value under market-based dispatch rises by an even greater amount, roughly $26 per kWh on average, thus the value gap widens
- Prices in NREL's Cambium model become more volatile over time as RE penetration increases, manifesting partly in terms of rising capacity prices
- When limited to solar self-consumption (and thus only discharged to meet onsite load), storage remains unable to capture much of the market value associated with occasional price spikes



Notes: The figure shows changes in projected storage dispatch value from 2020 to 2050, when operated either to maximize solar self-consumption under a net billing tariff with time-invariant rates or to maximize its market value. The value under each dispatch scheme and time period is computed for 24 distinct residential load profiles in each of the 15 locations shown, and the values plotted are averages across those individual profiles.

Conclusions

Conclusions

- Transition from NEM to net billing fails to anticipate the effects of battery storage
  - Potential for significant deadweight loss: large customer outlays for storage equipment that provides little societal benefit
  - Undermines the intent of NEM reforms: Moving solar grid exports back behind the meter maintains the same sales/revenue erosion issues as with NEM
  - Perpetuates inequities: Using storage to arbitrage between grid export prices and retail rates creates a new cost shift; beneficiaries skew toward even higher-income customers than stand-alone solar adopters
- To some extent, these issues could be mitigated through net billing designs that allow or incentivize customers to discharge to the grid during the highest value hours
  - Could also be done by coupling net billing with other programs
  - Requires consideration of, and potential tradeoffs with, local distribution network impacts

Contacts

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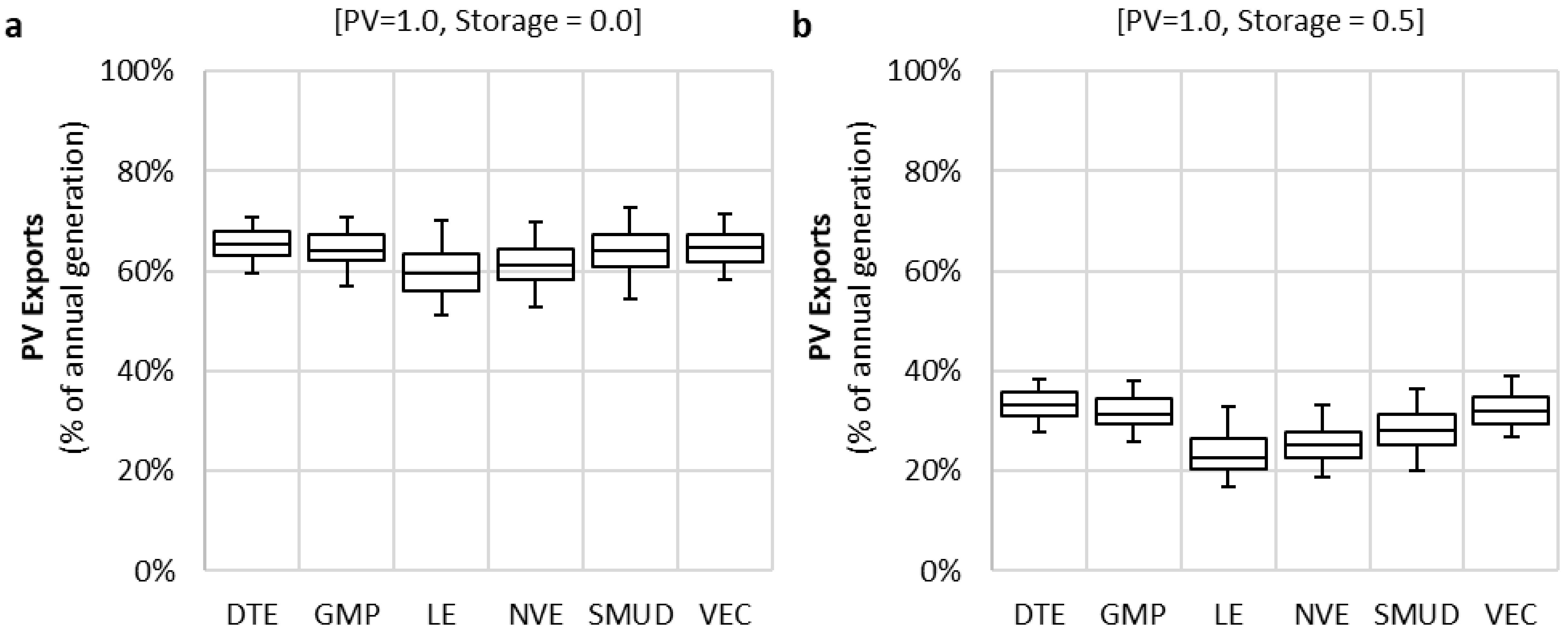
PV Export Levels across Individual Households



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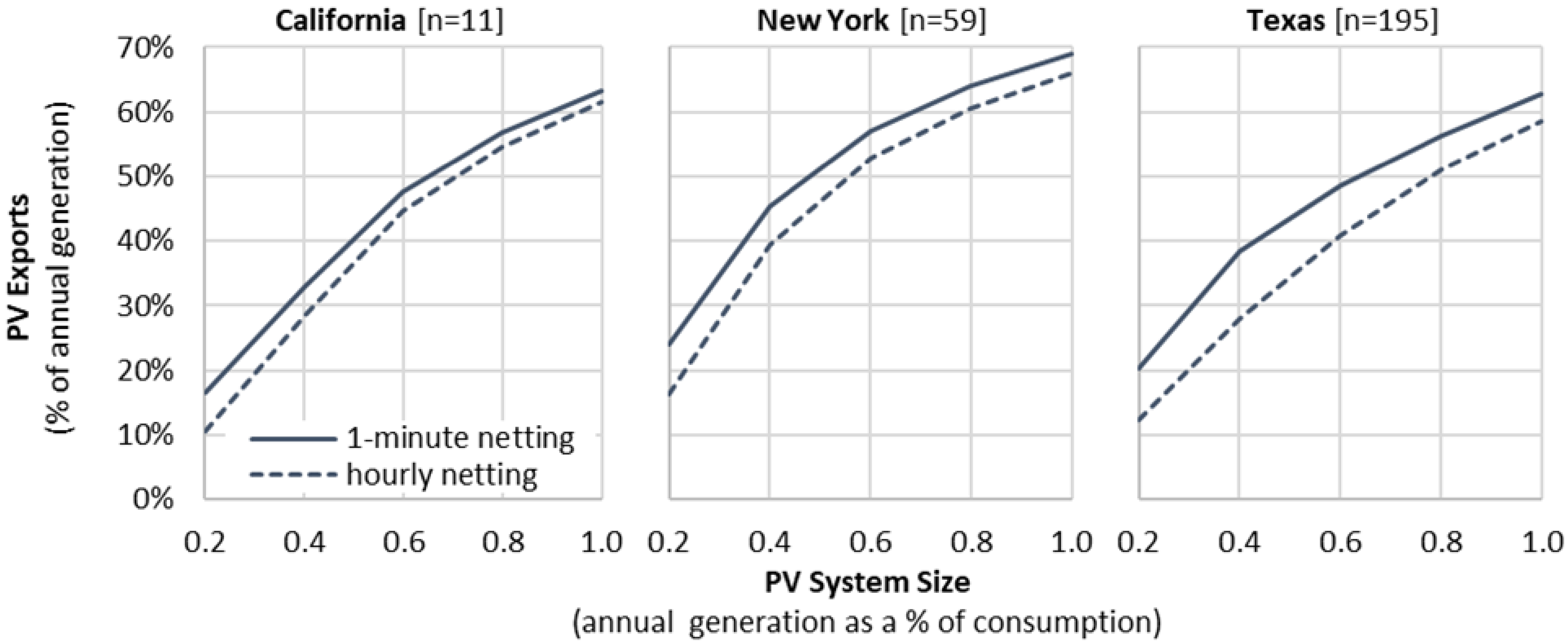
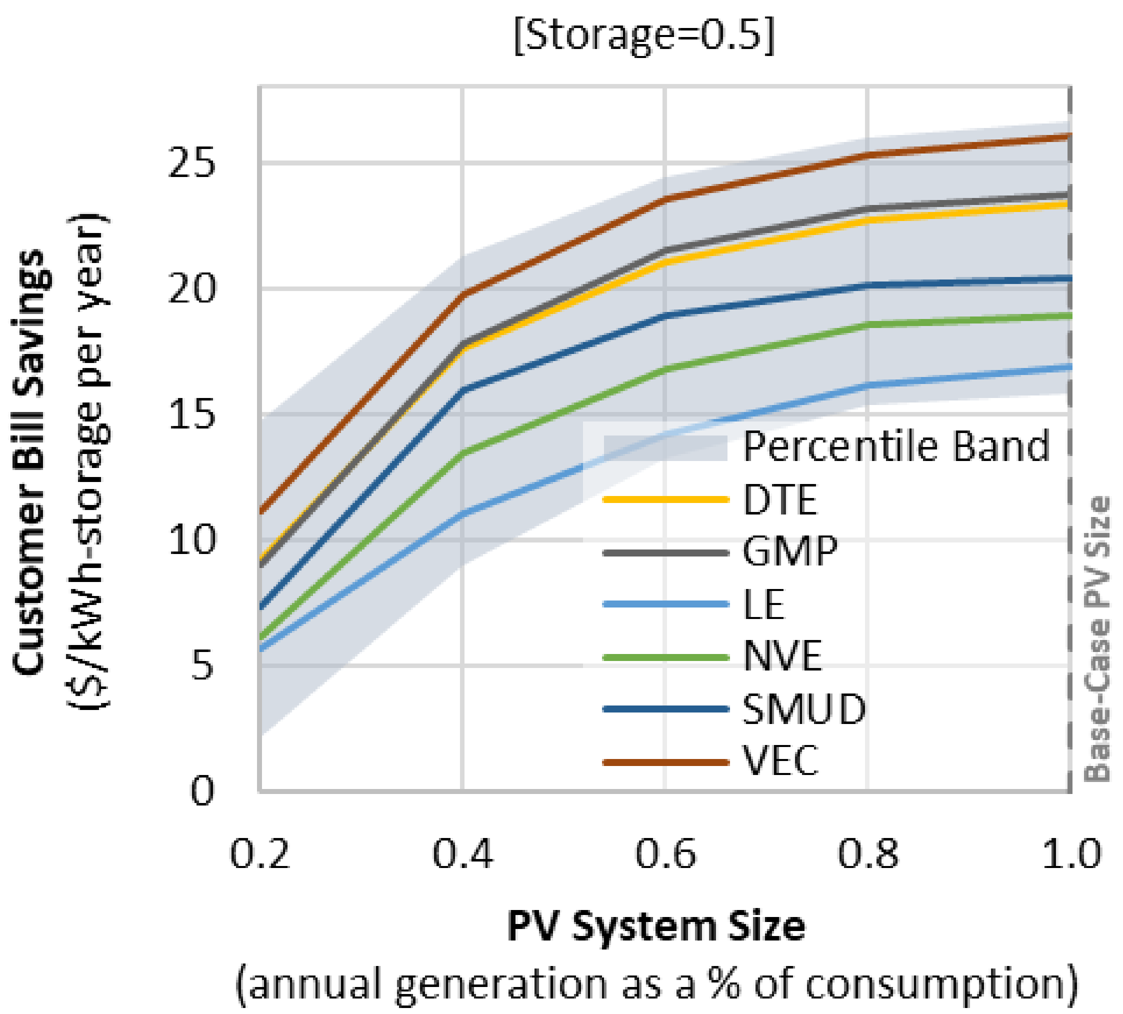
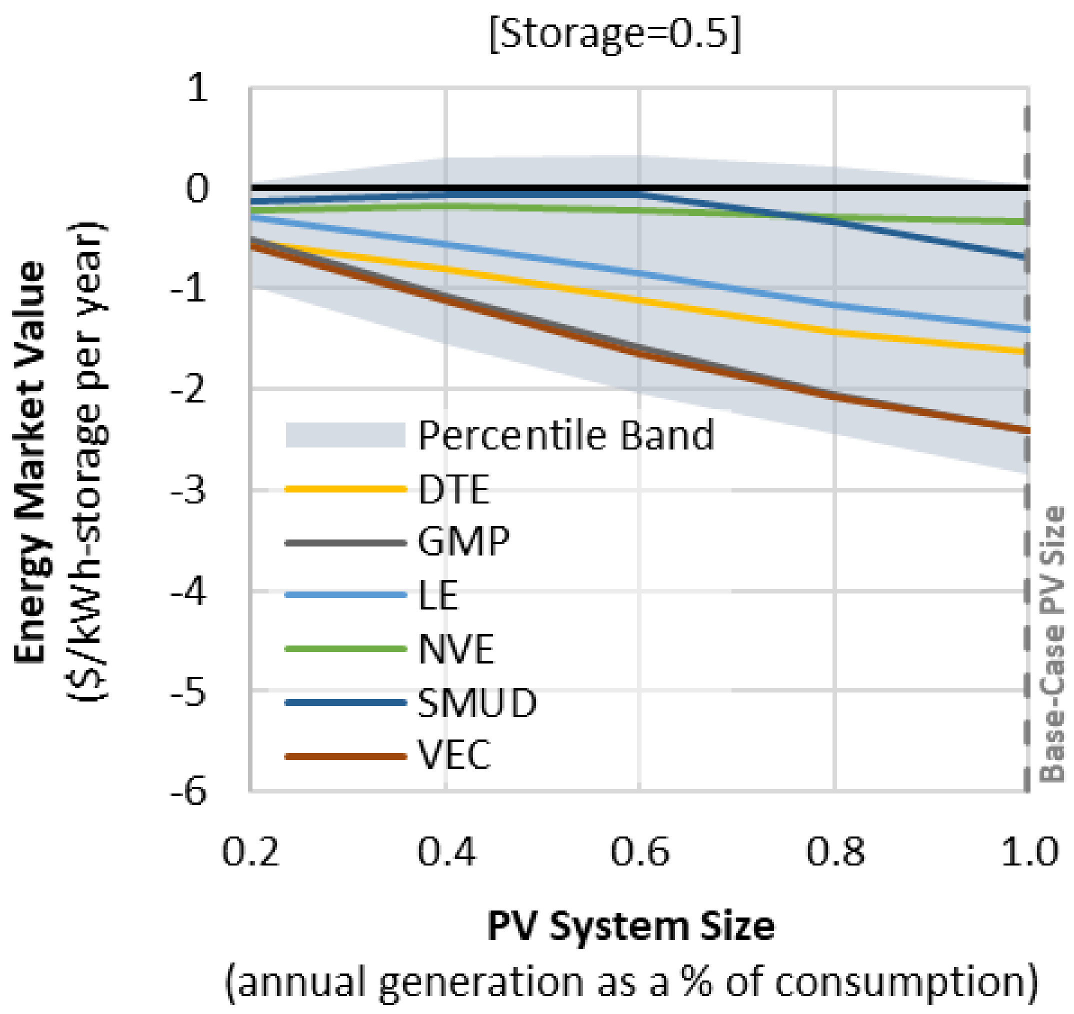
Netting over 1-Minute Intervals Yields Slightly Higher Export Levels than Hourly Netting (using Pecan Street data)

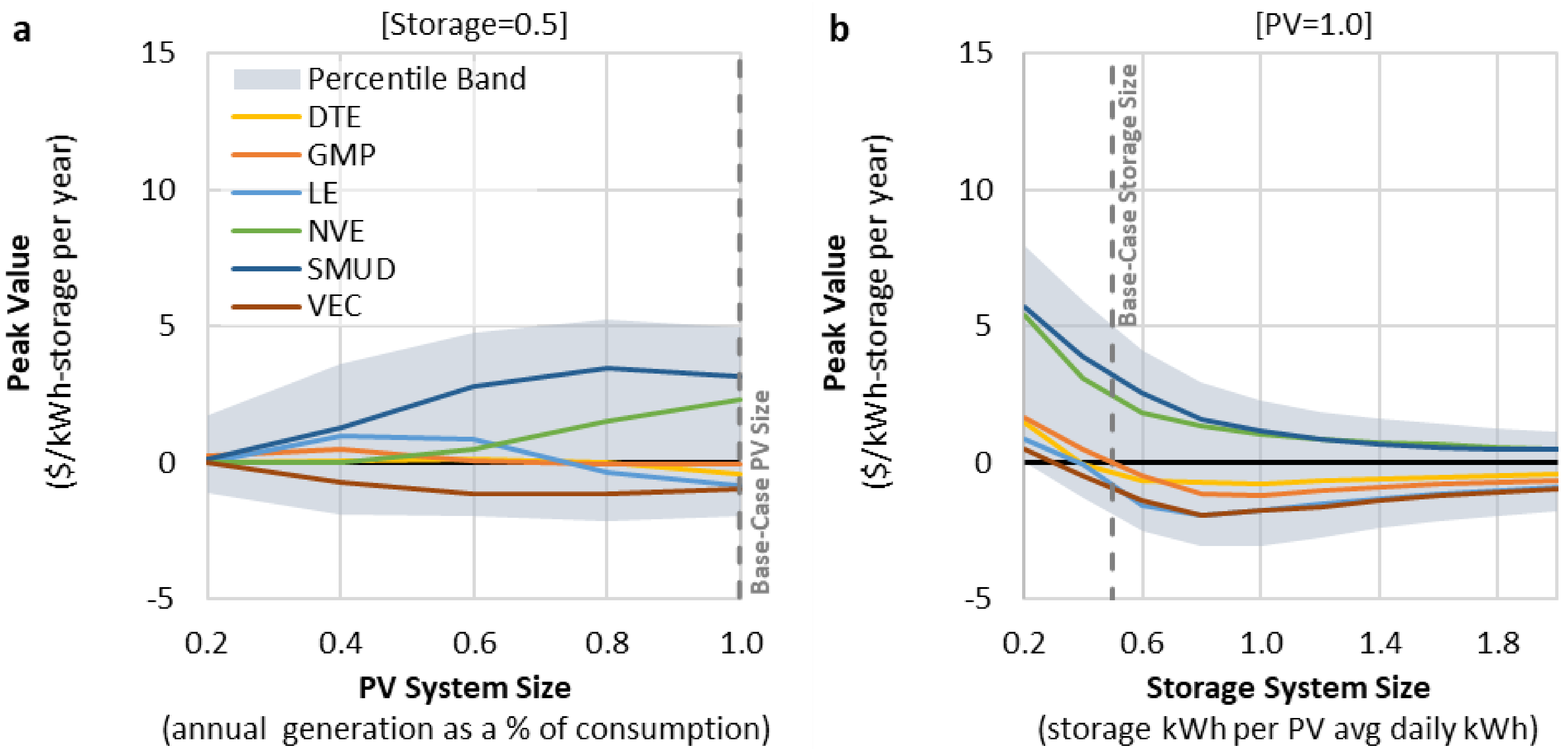


Customer Bill Savings & Energy Market Value of Storage Operated for Solar Self-Consumption: Sensitivity to PV System Size

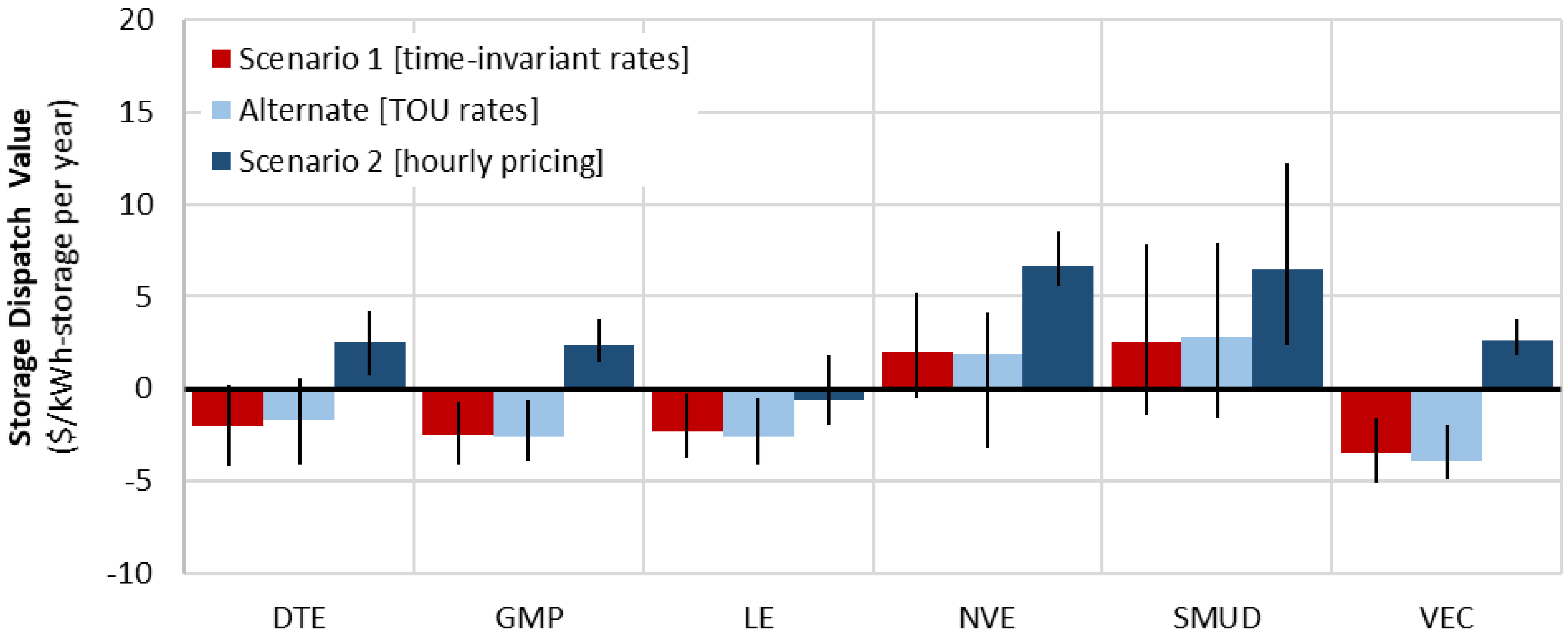




Peak Value of Storage Operated for Solar Self-Consumption: Sensitivities to PV and Storage System Size



Storage Dispatch Value with TOU-Based Export and Consumption Prices



Storage Dispatch Value with Alternate Sequencing of Grid Charging and Discharging Scenarios